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SUPER-SOLAR SUPER LYMAN LIMIT SYSTEMS

Jason X. Prochaska[1,2], John M. O'Meara[3], Stéphane Herbert-Fort[2,4] Scott Burles[3], Gabriel E. Prochter[1,2], and Rebecca A. Bernstein[5]

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ABSTRACT

We present abundance measurements for two super Lyman Limit systems (SLLS; quasar absorption line systems with $10^{19}\,\mathrm{cm}^{-2} < N_{\rm HI} < 10^{20.3}\,\mathrm{cm}^{-2}$) selected from a set of metal-strong absorbers in the Sloan Digital Sky Survey quasar database. After applying estimate corrections for photoionization effects, we derive gas-phase metallicities of [M/H]=$+0.7 \pm 0.2$ dex for the SLLS at $z = 1.7749$ toward SDSS0927+5621 and [M/H]=$+0.05 \pm 0.1$ dex for the SLLS at $z = 1.7678$ toward SDSS0953+5230. The former exhibits among the highest gas metallicity of any astrophysical environment and its total metal surface density exceeds that of nearly every known damped Lyα system. The properties of these absorbers – high metallicity and large velocity width ($\Delta v > 300$ km s^{-1}) – resemble those of gas observed in absorption in the spectra of bright, star-forming galaxies at high redshift. We discuss the metal mass density of the SLLS based on these observations and our ongoing SLLS survey and argue that a conservative estimate to the total metal budget at $z = 2$ is greater than 15% of the total, suggesting that the metal-rich LLS may represent the dominant metal reservoir in the young universe.

Subject headings: quasars : absorption lines

1. INTRODUCTION

With the recent successes of high redshift galaxy surveys, the star formation history of the young universe is revealing itself (Madau *et al.* 1996; Giavalisco *et al.* 2004). Although debate continues on various aspects of the measurements (e.g. dust extinction, sample selection, sample variance), it is evident that the star formation rate at $z > 2$ was substantially higher than the current epoch. Accordingly, the massive stars which light up these galaxies must have produced copious metals and redistributed them via supernovae to the galaxy and surrounding medium. A valuable test of this picture, therefore, is to obtain an accurate census of metals at $z \approx 2$ and compare against the amount predicted by the integrated the star formation history (Pagel 2002; Pettini 2004; Bouché, Lehnert & Péroux 2005). In the following, we will adopt a metal mass density at $z = 2$ of $\Omega_m^{Total} = 3 \times 10^{-5} h_{70}^{-2}$ based on the work of Bouché, Lehnert & Péroux (2006).

Prior to these galaxy surveys, analysis of heavy metals in quasar absorption line (QAL) systems – the gas within and in between high z galaxies – demonstrated that star formation was ubiquitous at $z > 2$ (Tytler *et al.* 1995; Wolfe *et al.* 1994; Pettini *et al.* 1994). Metals are present in excess of the primordial value throughout much of the universe (Schaye *et al.* 2003; Simcoe, Sargent & Rauch 2004; Bergeron & Herbert-Fort 2005) and a direct census of the intergalactic medium (IGM) adds up to $5 - 15\%$ of Ω_m^{Total}(Pettini 2004; Schaye *et al.* 2003). Regarding the interstellar medium of galaxies, the damped Lyα systems (QAL systems with $N_{\rm HI} \geq 2 \times 10^{20}\,\mathrm{cm}^{-2}$) offer the most direct means of measurement (Pettini *et al.* 1994; Prochaska *et al.* 2003). Surveys of these absorption systems have demonstrated that the metals associated with H I gas in DLAs contribute as comparable a fraction as the IGM probed through the Lyα forest. The metals in stars can be estimated from the luminosity functions and metallicity estimates of galaxy surveys; Bouché, Lehnert & Péroux (2006) estimates this contributiotn to be $20 - 50\%$ at $z = 2$. Altogether the census of metals in the IGM, the ISM probed by DLA, and stars falls short by as much as 70% of Ω_m^{Total}.

At present, there are several suggested explanations for this discrepancy. These include: (1) a significant portion of the metals are within dusty neutral gas (possibly molecular) which obscures any background quasar avoiding detection (Fall & Pei 1993; Vladilo & Péroux 2005), (2) a significant fraction of metals are sequestered within a hot, diffuse, collisionally ionized gas, which is difficult to probe with rest-frame ultraviolet transitions (Ferrara, Scannapieco & Bergeron 2005), (3) metals (primarily O VI) are locked in warm–hot gas (Simcoe, Sargent & Rauch 2002), or (4) metals are located in high metallicity "feedback" systems (Simcoe *et al.* 2006). All of these phases are certain to contribute, some to a larger extent than others, and it is possible that a complete solution will include significant contributions from each.

In this paper, we wish to highlight another reservoir of metals: highly photoionized, yet optically thick absorption systems. Specifically, we wish to examine the possible contribution from the Lyman Limit systems (LLS; absorbers with $N_{\rm HI} > 10^{17.2}\,\mathrm{cm}^{-2}$ and restricted here to have $N_{\rm HI} < 10^{20.3}\,\mathrm{cm}^{-2}$), the heretofore neglected sibling of the QAL systems. While the intergalactic medium examines gas arising in regions with overdensity $\delta \equiv \rho/\bar{\rho} < 10$ and the damped Lyα systems describe gas in overdense ($\delta > 200$) galactic regions, the LLS are likely to represent the interface between dense galactic and tenuous in-

[1]Department of Astronomy and Astrophysics, UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064

[2]Visiting Astronomer, W.M. Keck Observatory which is a joint facility of the University of California, the California Institute of Technology, and NASA

[3]MIT Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge MA 02139

[4]University of Arizona/Steward Observatory, 933 N Cherry Avenue, Tucson, AZ 85721

[5]Department of Astronomy, University of Michigan, Ann Arbor, MI 48109

tergalactic gas. It is reasonable to speculate that these absorbers probe gas related to galactic feedback processes and could therefore be a significant metal reservoir. The IGM and DLA systems have been surveyed extensively for metals (Schaye *et al.* 2003; Simcoe, Sargent & Rauch 2004; Prochaska *et al.* 2003) but analysis of the LLS has been limited to a few systems (Prochaska 1999; Prochaska & Burles 1999) and a small survey of super Lyman limit systems (SLLS), systems with $N_{\rm HI} = 10^{19} - 10^{20.3}\,{\rm cm^{-2}}$ (Dessauges-Zavadsky *et al.* 2003; Péroux *et al.* 2003, 2005). Because even the SLLS outnumber DLA by approximately a factor of four, the LLS could easily contribute a significantly larger metal mass than the DLA.

To make a direct comparison, one must consider the frequency distribution, ionization state, and mean metallicity of the LLS, all of which are poorly constrained. In this Letter, we will consider the current constraints and highlight the prospective importance of the SLLS. Péroux *et al.* (2006) have recently presented measurements on a low redshift SLLS which shows a super-solar metallicity[6] and the authors proposed that similar absorbers at high redshift could contain an important fraction of the metal budget. Here, we report on two super-solar SLLS at $z_{abs} = 1.8$ drawn from our survey of metal-strong DLA candidates (Herbert-Fort *et al.* 2006) and an on-going survey of LLS. The more extreme of the two systems exhibits greater than 5 times solar metallicity and has a metal surface density which matches all of the DLA with metallicity measurements at $z = 1.6$ to 2.2. We will argue that the LLS are likely to account for at least 15% of the metal budget at high redshift and possibly the remainder of 'missing' metals.

2. OBSERVATIONS AND CHEMICAL ABUNDANCES

Herbert-Fort *et al.* (2006) have recently published a survey for QAL systems with very large metal-line column densities (termed metal-strong DLA candidates) from the Sloan Digital Sky Survey database (Abazajian *et al.* 2005). The overwhelming majority of these absorbers are metal-strong damped Lyα systems (MSDLA), yet follow-up observations have revealed that a small fraction have $N_{\rm HI} < 2 \times 10^{20}\,{\rm cm^{-2}}$. Two examples include the SLLS at $z \approx 1.8$ toward quasars SDSSJ0927+5621 and SDSSJ0953+5230 (hereafter, SLLS0927+5621 and SLLS0953+5230).

We observed the quasars SDSSJ0927+5621 and SDSSJ0953+5230 on UT 13 April 2005 and 17 March, 2005 for total exposure times of 7200s and 8400s respectively with the upgraded HIRES spectrometer (Vogt *et al.* 1994) on the Keck I telescope. In each case, we employed the C5 decker (1.1″ wide) giving a FWHM$\approx$ 8 km s^{-1} resolution and chose a cross-disperser angle which gave wavelength coverage $\lambda \approx 3150 - 6000$Å. We reduced the 2D images with the HIRES Redux pipeline[7] and extracted, coadded and normalized the 1D spectrum with the software. The spectra have a signal-to-noise ratio of ≈ 7 per 2.6km s^{-1} pixel at 3400Å.

We have measured the H I column density of these SLLS by fitting Voigt profiles to the Lyα transitions (Figure 1). For SLLS0953+5230 (Figure 1b), damping wings are obvious and a precise evaluation of $N_{\rm HI}$ is straightforward, albeit subject to uncertainty dominated by continuum placement. In the case of SLLS0927+5621, the absence of significant damping wings limits $N_{\rm HI} < 10^{19.2}\,{\rm cm^{-2}}$. In Figure 1a, we present a fit constructed by distributing the neutral hydrogen according to the observed metal-line profiles. The best-fit total hydrogen column density is $10^{19.0}\,{\rm cm^{-2}}$, but we caution that a significantly lower column density is permitted by the data. Figure 2 presents a subset of the metal-line transitions observed for the two absorbers. We have measured column densities for all the transitions using the apparent optical depth method (Savage & Sembach 1991) and list the values and errors in Table 1. At HIRES resolution, the profiles are well resolved and there is no indication of 'hidden' line saturation from column density measurements of multiple transitions of the same ion.

The metallicity of the SLLS may be derived by comparing the metal column densities against $N_{\rm HI}$. In gas that is predominantly neutral (e.g. the majority of DLA), an accurate metallicity value is calculated through a direct comparison of low-ion species, e.g. ${\rm Si/H} \approx {\rm Si^+/H^0}$. In systems with predominantly photoionized gas, however, one must consider ionization corrections to the low-ion ratios (Howk & Sembach 1999; Vladilo *et al.* 2001; Prochaska *et*

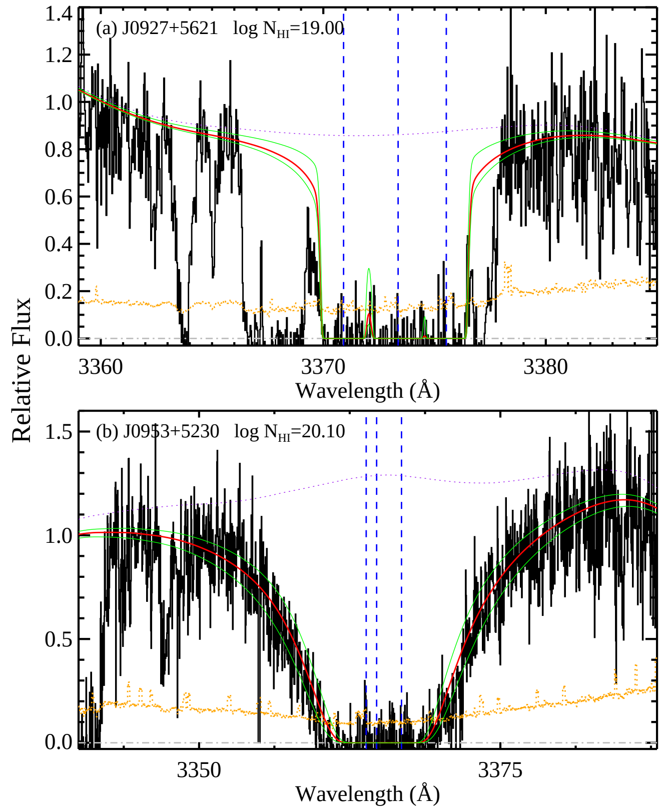

FIG. 1.— Lyα profiles of the SLLS at (a) $z = 1.775$ toward SDSS0927+5621 and (b) $z = 1.768$ toward SDSS0953+5230. The dotted curves indicate our estimate of the quasar continuum convolved with the blaze function of the HIRES spectrometer. The dashed vertical lines indicate the redshift of 'clouds' included in our best-fit solution (solid red line).

[6]One notes that Rao, Turnshek & Nestor (2006) measured this absorber to have log $N_{\rm HI} = 20.5$ and therefore identified it as a DLA system. Our analysis of the HST/STIS spectra gives log $N_{\rm HI} = 20.3 \pm 0.2$.

[7]http://www.ucolick.org/~xavier/HIRedux/index.html

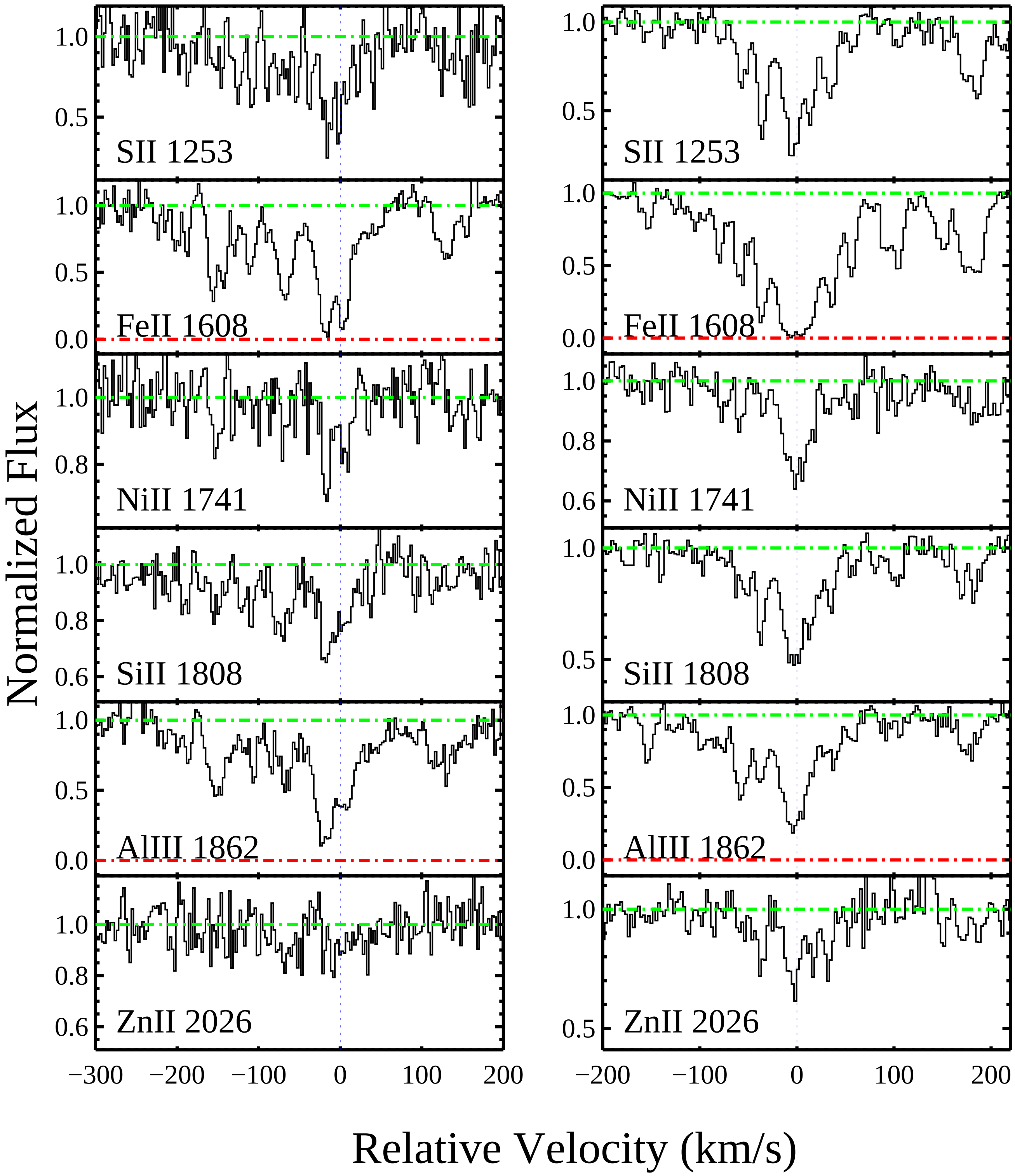

FIG. 2.— Velocity profiles of a subset of the metal-line transitions observed for the SLLS at LHS: $z = 1.7749$ toward SDSS0927+5621 and RHS: $z = 1.7678$ toward SDSS0953+5230.

Table 1
IONIC COLUMN DENSITIES

Ion	λ	J0927+5621			J0953+5230		
		flg[a]	$\log N$	$\log N^b_{adopt}$	flg[a]	$\log N$	$\log N^b_{adopt}$
H I	1215.67	1		$19.00^{+0.10}_{-0.25}$	1		$20.10^{+0.10}_{-0.10}$
C II	1334.532	3	> 15.49	> 15.49	3	> 15.62	> 15.62
C IV	1548.195	2	> 15.31	> 15.52	2	> 15.22	> 15.31
C IV	1550.770	2	> 15.52		2	> 15.31	
N I	1199.550				3	> 14.92	> 14.92
N V	1242.804				0	13.33 ± 0.11	13.33 ± 0.11
O I	1302.168	3	> 15.71	> 15.71	3	> 15.86	> 15.86
O I	1355.598				5	< 17.91	
Al II	1670.787	3	> 14.02	> 14.02	3	> 14.13	> 14.13
Al III	1854.716	2	> 13.93	14.05 ± 0.01			13.86 ± 0.01
Al III	1862.790	0	14.05 ± 0.01		0	13.86 ± 0.01	
Si II	1264.738	4	< 12.61	15.58 ± 0.02	4	< 11.97	15.67 ± 0.01
Si II	1304.370	3	> 15.37		3	> 15.46	
Si II	1526.707	3	> 15.23		3	> 15.34	
Si II	1808.013	1	15.58 ± 0.02		1	15.67 ± 0.01	
Si III	1206.500	2	> 14.41	> 14.41	2	> 14.46	> 14.46
Si III	1892.030	4	< 16.70		4	< 16.39	
Si IV	1393.755	2	> 14.75	> 14.92	2	> 14.61	> 14.60
Si IV	1402.770	2	> 14.92		2	> 14.60	
P II	1152.818			< 14.33	3	> 14.14	> 14.14
P II	1532.533	5	< 14.33		5	< 14.14	
S II	1250.584			15.29 ± 0.04	1	15.36 ± 0.02	15.35 ± 0.01
S II	1253.811	1	15.29 ± 0.04		1	15.35 ± 0.01	
Cr II	2056.254	5	< 12.97	< 12.97	1	13.18 ± 0.08	13.18 ± 0.08
Cr II	2066.161				5	< 13.12	
Fe II	1608.451	3	> 14.86	15.28 ± 0.13	3	> 15.09	14.99 ± 0.10
Fe II	1611.200	1	15.28 ± 0.13		9	14.99 ± 0.10	
Ni II	1370.131			13.75 ± 0.09	1	13.88 ± 0.03	14.05 ± 0.04
Ni II	1454.842	1	13.66 ± 0.08		1	13.89 ± 0.04	
Ni II	1709.604				1	14.08 ± 0.04	
Ni II	1741.553	1	13.75 ± 0.09		1	14.11 ± 0.03	
Ni II	1751.916				1	14.05 ± 0.04	
Zn II	2026.136	5	< 12.62	< 12.62	1	12.89 ± 0.04	12.89 ± 0.04

[a]Flag: 0=Non-dominant ion or blended transition. 1=Dominant ion; 2=Saturated, non-dominant ion; 3=Saturated, dominant ion 4=Upper limit, non-dominant ion; 5=Upper limit, dominant ion.
[b]Weighted mean or most stringent limit.

Note. — Column densities are measured from the apparent optical depth method integrated over the entire line-profile.

al. 2002). To gauge the ionization state, ideally one compares multiple ionization levels of a single element. Unfortunately, the relatively low redshift of these SLLS places several key transitions (e.g. Fe III 1122, N II 1083) below the atmospheric cutoff. One can, however, make a first crude estimate based on the $N_{\rm HI}$ values. At $z \sim 2$, the extragalactic background radiation field is sufficiently intense to photoionize the majority of absorbers with $N_{\rm HI} < 10^{19.5}$ (Viegas 1995; Prochaska & Wolfe 1996). Therefore, we expect that SLLS0927+5621 is predominantly ionized with ionization fraction $x \equiv {\rm H^+/H} > 0.5$, perhaps with an ionization state comparable to the SLLS at $z = 2.65$ toward Q2231–00 ($x = 0.99$; Prochaska 1999). At $N_{\rm HI} = 10^{20.10}$, SLLS0953+5230 is nearly a DLA and one expects it to have a much lower ionization fraction than SLLS0927+5621.

The observations place an additional constraint on the ionization fraction. First, we have measured $N({\rm Al^{++}})$ values from the Al III 1862 transitions and set an upper limit on the ${\rm Al^{++}/Al^+}$ ratios based on the saturated Al II 1670 profile (Table 2). These values, unfortunately, are not very constraining and allow for both large and small x values. Vladilo *et al.* (2001) have shown that the ${\rm Al^{++}/Si^+}$ ratio is a useful diagnostic of photoionization. The observed ${\rm Al^{++}/Si^+}$ value for SLLS0927+5621 is twice as large as that for any DLA whereas the value for SLLS0953+5230 is comparable to that for DLA with low $N_{\rm HI}$ value (Vladilo *et al.* 2001). Therefore, the values are consistent with a significant ionization fraction for SLLS0927+5621 and predominantly neutral gas for SLLS0953+5230. As such, we estimate the ionization corrections for SLLS0953+5230 are negligible.

For SLLS0927+5621, we have considered the ionization corrections in greater depth. Specifically, we have performed a series of Cloudy calculations (v05.07.06 Ferland 2003) assuming a constant density cloud with $N_{\rm HI} = 10^{18}\,{\rm cm^{-2}}$ to $10^{19}\,{\rm cm^{-2}}$, solar metallicity and two input radiation fields: (i) an updated extragalactic UV background (EUVB) model (HM; Haardt & Madau 1996) and (ii) the output from a Starburst 99 calculation (SB99; Leitherer *et al.* 1999) for a galactic starburst with age of 100 Myr. As discussed below, the latter radiation field is motivated by the fact that these SLLS absorbers resemble the gas associated with bright Lyman break galaxies (Steidel *et al.* 1999; Pettini *et al.* 2002). We considered a range of intensities parameterized by the ionization parmeter $U \equiv \phi/n_H$ with ϕ the number density of ionizing photons. For the HM model and $N_{\rm HI} = 10^{19}\,{\rm cm}^{-2}$, the upper limit to Al^{++}/Al^{+} implies upper limits to the ionization corrections for Si^{+} and Fe^{+} of 0.6 dex and 0.2 dex respectively. We note, however, that the Al II 1670 profile is highly saturated and a more reasonable upper limit to $\log(Al^{++}/Al^{+})$ is -0.3 dex implying ionization corrections of less than 0.3 dex for all of the low-ions considered here. To be conservative, we have adopted 0.3 dex corrections, i.e. (X/H) = (X^i/H I) -0.3, for all low-ions X^i.

If one were to assume a lower $N_{\rm HI}$ value for SLLS0927+5621, the ionization correction is larger but the corrected gas metallicity is also larger (the increased ionization correction is smaller than the decrease in $N_{\rm HI}$). Similarly, if we adopt the S99 spectrum which is softer than the EUVB field one also finds slightly larger corrections (0.1 to 0.2 dex). However, the corrections for $\log(Al^{++}/Al^{+}) \approx -0.3$ are still only ≈ 0.3 dex for Si^{+} and S^{+} relative to H I. We caution again that one should avoid drawing firm conclusions on the ionization state of the gas from Al^{++} and Al^{+} alone because of uncertainties in the recombination rates of these ions. Unfortunately, a more accurate assessment of the ionization corrections must await observations at $\lambda < 3000$Å.

Table 2
SUMMARY

	J0927+5621	J0953+5230
$z_{\rm SLLS}$	1.775	1.768
$N_{\rm HI}$	$19.00^{+0.10}_{-0.25}$	$20.10^{+0.10}_{-0.10}$
[Si/H][a]	+0.72	+0.01
[S/H]	+0.79	+0.05
[Zn/H]	< +0.65	+0.12
[S/Fe]	+0.31	+0.66
$\log(Al^{++}/Al^{+})$	< 0.02	< −0.27
$\log(Al^{++}/Si^{+})$	−1.53	−1.81
x^b	0.9	< 0.1

[a] [X/Y] is the logarithmic gas-phase abundance of species X relative to Y relative to Solar abundance. We have assumed low-ion species and ionization corrections of 0.3 dex for SLLS0927+5621 and 0 dex for SLLS0953+5230.
[b] Adopted value based on inferences made from the observed $N_{\rm HI}$ and Al^{++} values.

Table 2 presents the gas-phase abundances relative to solar (Grevesse, Noels & Sauval 1996) based on the low-ion ratios with our adopted ionization corrections. The Zn[8], Si, and S values for SLLS0927+5621 are all consistent with the absorber having $\approx 5\times$ solar abundance. At present, the gas has the highest, precise metallicity measurement in any astrophysical environment (e.g. Dietrich *et al.* 2003; Jenkins *et al.* 2005; Péroux *et al.* 2006; Gratton *et al.* 2006; Pilyugin *et al.* 2006). Again, we note that the H I column density could be significantly less than the value adopted here. If we adopted a lower $N_{\rm HI}$ value we would derive a higher ionization fraction and ionization correction, yet also a higher gas metallicity.

[8] Note that Zn is a trace element and even a 100× enhancement would not require a large metallicity.

For SLLS0953+5230, the metallicity is marginally super-solar. The observations demonstrate that super-solar gas exists at high redshift, even apart from the direct vicinity of quasars.

3. DISCUSSION

Before commenting on the implications for metals in the young universe, let us consider the physical origin of this gas. It is notable that both absorbers exhibit relatively wide absorption line profiles revealing a velocity field of several hundred km s^{-1} . While this is partly the effect of selection bias (large velocity width yields larger EW), the MSDLA candidate sample (Herbert-Fort *et al.* 2006) focused primarily on Si II 1808 and Zn II 2026 which are optically thin in these systems. We suggest that the kinematics are indicative of feedback processes correlated with star formation. Indeed, these absorbers may represent sightlines which pass through the gas observed in absorption in the spectra of bright Lyman break galaxies (Steidel *et al.* 1999; Pettini *et al.* 2002). The systems also exhibit very large C IV column density. Current measurements of the frequency distribution of C IV column densities show a dependence $N_{\rm CIV}^{-\alpha}$ with $\alpha < 2$ to C IV column densities of $N_{\rm CIV} = 10^{15}\,{\rm cm}^{-2}$ (Songaila 2005). Therefore, the mass density of C^{+3} ions is dominated by the largest column density absorbers. We suspect that LLS like the ones presented here contain the majority of C^{+3} ions at all redshifts. Again, this is an assertion we will test through a large sample of LLS observations. It would be valuable to compare the observations of the super-solar SLLS with models of outflows from star-forming galaxies.

The detection of two super-solar SLLS underscores the prospect for LLS to contain a substantial fraction of the metal mass in the high z universe. Consider the results for SLLS0927+5621 alone. The total metal column density of the gas is given by $\log N_M = \log N_H + \log(M/H)$ where N_H is the total hydrogen column density and M/H is the mean metallicity of the gas. Taking $x = 0.9$ ($N_H = 10 N_{\rm HI}$) and five times solar abundance, we find that the metal column density is 50% larger than any DLA at $z \approx 2$. In fact, the N_M value roughly matches the total of the ≈ 20 DLA with metallicity measurements at $z = 1.6$ to 2.2 (Prochaska *et al.* 2003). Because SLLS outnumber DLA by ≈ 4 times (O'Meara *et al.* 2006), even if systems like SLLS0927+5621 represent only 1% of the SLLS population, their contribution would match the entire DLA population. This remains true even if the other 99% of SLLS were primordial!

To better illustrate the contribution of LLS (specifically SLLS) on the cosmological metal budget, consider the following calculation. First, define the mass density of metals in the DLA relative to the critical density

$$\Omega_m^{DLA} = \Omega_{HI}^{DLA} \bar{Z}_{DLA} \qquad (1)$$

where $\bar{Z}_{DLA}$ is the mean metallicity in mass units (i.e. $Z_\odot = 0.022$ is the Solar metallicity). Adopting the results from Prochaska, Herbert-Fort & Wolfe (2005) $\Omega_{HI}^{DLA} = 0.5 \times 10^{-3}$ and Prochaska *et al.* (2003) $\bar{Z}_{DLA} = 0.0022$, we derive $\Omega_m^{DLA} = 1.1 \times 10^{-6}$, i.e. a few percent of Ω_m^{Total}.

Consider the metal mass density of the SLLS, Ω_m^{SLLS}, motivated by observational considerations:

$$\Omega_m^{SLLS} = \int \frac{1}{1-x} N_{\rm HI} f(N_{\rm HI}) \bar{Z}_{SLLS}\, dN_{\rm HI} \qquad (2)$$

where x is the ionization fraction of the LLS (likely a function of $N_{\rm HI}$), f is the frequency distribution, and $\bar{Z}_{LLS}$ is the mean metallicity of the gas. Currently, all of the expressions in the integrand of Equation 2 are poorly constrained and so we will proceed conservatively. First, we adopt our new measurement of $f_{\rm HI}(N_{\rm HI})$ for the SLLS at $z \approx 2.5$ (O'Meara *et al.* 2006): $f_{\rm HI}(N_{\rm HI}) = 10^{7.17} N_{\rm HI}^{-1.4}$. Second, we will adopt a value to the mean metallicity based on the Péroux *et al.* (2003) survey ($\bar{Z}_{SLLS} = 0.1 Z_\odot$) and assume the value is independent of $N_{\rm HI}$ value. In light of the results presented in this paper, we consider this to be a conservative lower limit to $\bar{Z}_{SLLS}$. Even though super-solar SLLS are very rare they will contribute significantly to the mean if they represent $> 1\%$ of the sample.

The most uncertain quantity in this calculation is the ionization fraction which undoubtedly varies with $N_{\rm HI}$ column density (and possibly metallicity). Photoionization calculations estimate that $x \approx 0$ at the DLA threshold and increases to ≈ 0.9 at $N_{\rm HI} = 10^{19}\,{\rm cm^{-2}}$ with strongest dependence on the gas density and intensity of the radiation field (e.g. Vladilo *et al.* 2001; Prochaska *et al.* 2002). Péroux *et al.* (2003) and Dessauges-Zavadsky *et al.* (2003) stressed that ionization corrections are small for their SLLS sample and gave the misleading impression that the gas is predominantly neutral. Indeed, this is not the case (Dessauges-Zavadsky, priv. comm.); we also find that the SLLS can be significantly ionized (Prochaska 1999; Prochter et al. in prep.). For the following, we will parameterize x with an empirical motivation: $x = C_x(1 - N_{\rm HI}/10^{20.3})$ where C_x can be varied to reduce/increase the degree of photoionization.

Evaluating Equation 2, we derive $\Omega_m^{SLLS} = 5 \times 10^{-6} = 0.15 \Omega_m^{Total}$ for $C_x = 1$ and 2×10^{-6} for $C_x = 0.5$. These values are significantly in excess of the metal mass density implied by the damped Lyα systems and the IGM. We believe this calculation is reasonably conservative because (i) we have neglected the contribution of LLS with $N_{\rm HI} < 10^{19}\,{\rm cm^{-2}}$ and (ii) the mean metallicity of the SLLS could easily be 1/3 or 1/2 solar. Therefore, the LLS may contain the majority of metals at high z. In future papers, we will derive empirical measurements of the ionization fraction and metallicity of a large sample of LLS to directly determine the LLS contribution.

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